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VALUE ASSESSMENT TOOLS FOR HYBRID NDE-SHM LIFE MANAGEMENT STRATEGIES (PREPRINT)

Enrique A. Medina, John C. Aldrin, Jeremy S. Knopp, and Daniel A. Allwine

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AIR FORCE RESEARCH LABORATORY
AIR FORCE MATERIEL COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OH 45433-7750

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*//Signature//

JEREMY S. KNOPP
Project monitor / in-house author
Nondestructive Evaluation Branch
Metals, Ceramics and NDE Division

//Signature//

THOMAS J. MORAN
Technology Development Leader
Nondestructive Evaluation Branch
Metals, Ceramics and NDE Division

//Signature//

GERALD J. PETRAK, Asst Chief
Metals, Ceramics and NDE Division
Materials and Manufacturing Directorate

*Disseminated copies will show "//Signature//" stamped or typed above the signature blocks.

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John C. Aldrin and Daniel A. Allwine (Austral Engineering & Software, Inc.)
Enrique A. Medina and Jeremy S. Knopp (AFRL/MLLP)

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Austral Engineering & Software, Inc.
408 Richland Ave., Suite 102
Athens, OH 45701

Nondestructive Evaluation Branch (AFRL/MLLP)
Metals, Ceramics, and Nondestructive Evaluation Division
Materials and Manufacturing Directorate
Air Force Research Laboratory, Air Force Materiel Command
Wright-Patterson Air Force Base, OH 45433-7750

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14. ABSTRACT
A variety of structural health monitoring (SHM) technologies has been proposed in the last few years for enhancing the ability to manage the life of aircraft structures. This work builds upon prior efforts comprising the development and demonstration of a software platform for integrating NDE design and product life management models. Based on probabilistic models of fatigue crack growth, detection, and repair, the demonstration cases show the ability of the method and software to assess the effects that changes in inspection parameters and scheduling can have on time-dependent reliability and maintenance cost objectives. Furthermore, the software facilitates design tradeoff assessment and optimization for goals such as cost, reliability, and system availability. This paper describes the development of probabilistic model components representing SHM systems, to be integrated into a hybrid life management approach where SHM and NDE are complementarily utilized. Example design cases include 1) analysis of near- and long-term costs and benefits of SHM applications, considering time-dependent sensor reliability, to provide insight into the potential opportunities and challenges of SHM applications and 2) assessment of maintenance programs that combine NDE and SHM systems. Two case study examples are presented to illustrate the value of these decision support tools and models.

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ABSTRACT

A variety of structural health monitoring (SHM) technologies has been proposed in the last few years for enhancing the ability to manage the life of aircraft structures. This work builds upon prior efforts comprising the development and demonstration of a software platform for integrating NDE design and product life management models. Based on probabilistic models of fatigue crack growth, detection, and repair, the demonstration cases show the ability of the method and software to assess the effects that changes in inspection parameters and scheduling can have on time-dependent reliability and maintenance cost objectives. Furthermore, the software facilitates design tradeoff assessment and optimization for goals such as cost, reliability, and system availability. This paper describes the development of probabilistic model components representing SHM systems, to be integrated into a hybrid life management approach where SHM and NDE are complementarily utilized. Example design cases include (1) analysis of near- and long-term costs and benefits of SHM applications, considering time-dependent sensor reliability, to provide insight into the potential opportunities and challenges of SHM applications and (2) assessment of maintenance programs that combine NDE and SHM systems. Two case study examples are presented to illustrate the value of these decision support tools and models.

INTRODUCTION

This paper presents recent work on value assessment tools for aircraft structural life management strategies that combine nondestructive evaluation (NDE) methods with structural health monitoring (SHM) technologies. Life management practices for aircraft structures have traditionally depended on the use of non-destructive inspections (NDI) which are usually performed after fixed numbers of flight hours.

While these inspections can be costly and time consuming, they enable maintenance personnel to detect damage before it can lead to catastrophic failure and to make appropriate maintenance and repair decisions that can ensure the reliability and availability of the aircraft fleet. The fact that many aircraft are used well beyond their designed life makes it more important to implement effective life management processes. In recent years, the U.S. Department of Defense has been working on the implementation of Condition-Based Maintenance (CBM) and Condition-Based Maintenance Plus (CBM+) approaches to aircraft sustainment [1].

For the case of aircraft structures, the CBM initiative clearly describes the (possibly complementary) use of NDE (external tests) and SHM (embedded sensors) as part of maintenance plans that are based on system condition diagnostics and prognostics. To complement the pervasive use of NDE techniques in maintenance programs, a significant number of applications for embedded sensing for SHM are currently the subject of research and/or implementation [2, 3, 4, 5, 6]. Reference [7] discusses some of the reliability and cost benefits of SHM technologies and some of the challenges that must be overcome for success in SHM implementation. It is clear that additional progress in both NDE and SHM technologies is still necessary before the full benefits of CBM can be reaped. Moreover, it is also necessary to establish methodologies for assessing the value of developing and implementing various life management technologies based on NDE, SHM, or combinations of the two.

These value assessment tools are based on probabilistic models of damage evolution, detection, and repair, and on appropriate maintenance cost models. While prior work by other research groups has addressed probabilistic risk assessment of fatigue crack growth and fracture incorporating NDE [8, 9] and prognostics and health management system design tools [6], the work presented here addresses the need for design tools that facilitate the integration of models for sensing technologies, signal processing algorithms, damage growth, repairs, reliability, and cost. It aims to enable the analysis of (1) tradeoffs among NDE and SHM techniques and parameters and (2) sensitivity of reliability and cost with respect to variations in these techniques and parameters. Furthermore, it is intended that these tools provide guidance for generation of design alternatives and for evaluating the best NDE and SHM design scenarios directly in terms of important performance metrics such as reliability and cost. A recent research and development program supported by the U.S. Air Force Research Laboratory extended basic probabilistic risk management models and combined them with cost models for life management strategies to address a wider array of problems than those possible with previously existing models and tools [7, 10]. That program resulted in the Virtual NDE (VNDE) software package, which has the following capabilities: (1) use of object-oriented components for flexible modeling, (2) integration of independent modeling tools, (3) integration of signal processing algorithm development tools, and (4) assessment and optimization of reliability and cost tradeoffs within a probabilistic framework for design of complex maintenance and life management strategies incorporating NDE and SHM technologies.

This methodology enables value assessment by incorporating cost benefit analysis with probabilistic risk assessment to evaluate the overall value of a life management system. Design tradeoffs are examined from an economic service life management perspective where reliability and total aircraft structure sustainment costs are

quantified. The remainder of the paper is organized as follows. The next section defines the SHM system model to be used within an existing object-oriented architecture for design of life management strategies. The cost model used for SHM is also described. The following section presents two case studies that demonstrate the use of the SHM model on the problem of component life management in the presence of fatigue cracks at fastener sites on multi-layer structures. The final section provides some concluding remarks and ideas for further work.

PROBABILISTIC MODEL OF SHM SYSTEMS

This section presents the theory and software implementation of a probabilistic model for SHM systems. This effort builds upon prior work comprising the development of a strategy and software framework for integrating NDI design and product life management tools [7, 10]. The model is based on prior work by Berens et al., who developed a software tool, PROF, for probabilistic risk assessment of fatigue crack growth and fracture incorporating NDE [8]. The newly developed probabilistic model components represent a wide range of SHM system configurations and address the use of secondary inspections and SHM system degradation. Lastly, case studies are utilized to provide key insight into the potential benefits and pitfalls of SHM applications. The model addresses "direct" SHM systems capable of acquiring NDE-type data using embedded sensors to quantify the damage state of a structure. The term "direct" is used to differentiate these methods from indirect approaches that measure loading and environmental conditions data to be used with fracture mechanics models to predict the future damage state. The direct approach requires that the damage state be observable from the distributed sensors' data. In the remainder of this paper the term structural health monitoring and the acronym SHM refer to this direct method.

Figure 1 depicts a diagram of a generic SHM process. First, there are two time intervals to consider: one associated with each opportunity for decision on maintenance (indexed by i) to be performed in the field, and an in-service SHM data acquisition time interval (indexed by j) at which an assessment of the damage state can be performed. It is important to distinguish between these two time intervals, since data may be acquired and a damage state estimate may be obtained at a rate different than the rate corresponding to the opportunity for decisions on performing in-field maintenance in the form of secondary inspections and/or repairs. For each data acquisition time interval (j), data can be acquired from each sensor (indexed by k) in the array for a given number of samples (indexed by l). For example, the number of samples (l) may be large for the case of acoustic emission measurements for impact damage estimation or quite small for humidity sensors for corrosion monitoring. Starting with the raw data, signal processing and feature extraction algorithms are applied to filter and extract features as a set of scalar values (indexed by n). Signal classification can subsequently be applied to a database of feature vectors collected over time to estimate the damage state ($\hat{a}$) for each critical location (indexed by m). For each opportunity to assess the damage state and perform maintenance, a damage decision criterion is applied based on a maximum acceptable critical flaw size (a_{cr}). A database of damage state estimates ($\hat{a}$) from prior decision intervals and data

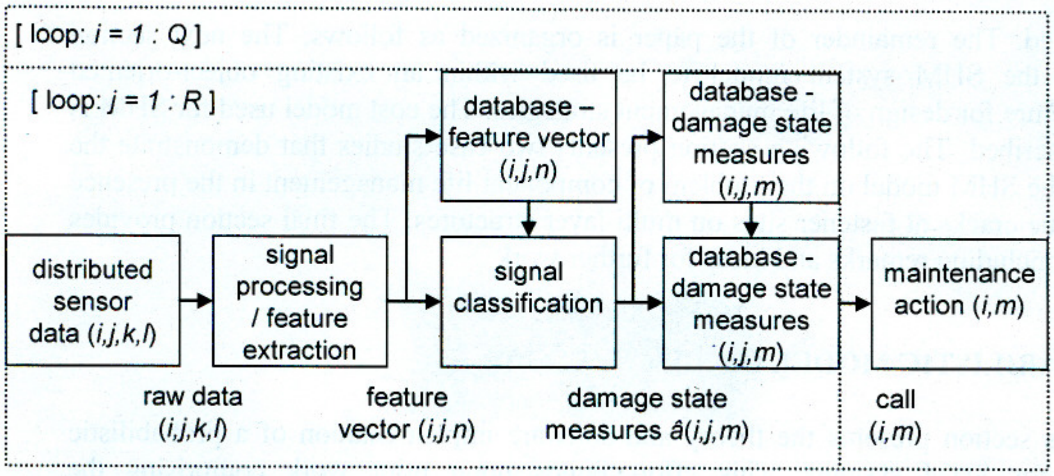

Figure 1. Flow diagram representation of an SHM system model identifying the analysis steps from sensor data to decision on a maintenance action such as a secondary inspection or repair.

acquisition periods (i,j) may be used in the decision process. The final step is the decision to perform a maintenance action such as a secondary inspection or repair.

From the perspective of quantifying the reliability of a SHM system, there is an underlying relationship that must be evaluated between the damage state estimate $(\hat{a})$ and the actual damage state (a), with special interest placed on the critical flaw size (a_{cr}) that prompts a maintenance action. This probability of detection (POD) assessment is no different from the "$\hat{a}$ versus a" analysis procedure previously devised for NDE systems [8]. Although a model-based approach including each analysis step for the SHM process shown in Figure 1 would be ideal, it is proposed, as a first approximation, to represent the relationship between the flaw size and the probability of detection, false call rate, and random missed flaw rate directly using a four parameter probability of detection model given by

$$POD(a,t) = \alpha(t) + (\beta(t) - \alpha(t))\left\{1 + \exp\left[-\frac{\pi}{\sqrt{3}}\left(\frac{\ln a - \ln \mu(t)}{\sigma(t)}\right)\right]\right\}^{-1}, \qquad (1)$$

where a is the flaw size, t is time, α corresponds to the false call rate, β is defined as one minus a random miss rate, σ controls the steepness of the probability of detection curve, and μ is the flaw size for which the probability of detection is 50%. Use of this four parameter POD model has been recommended to address the fact that both hits and misses are often made for reasons that are independent of crack length. Note that α, β, σ, and μ can be functions of time to represent changes in the characteristics of the SHM system during its service life. One commonly proposed advantage of SHM systems is that they can be installed at locations of difficult access. This makes it necessary to model and evaluate the effects of time-dependent variations on the response of the SHM system.

Figure 2 presents a flow diagram for a basic SHM system integrated with an in-service period, with the opportunity for in-field maintenance incorporating a secondary inspection and repair process (with $j = 1$). A probabilistic analysis methodology is utilized for evaluating the model component blocks 'Inspect 1 - SHM', 'Inspect 2 - NDE' and 'Repair' found in the figure.

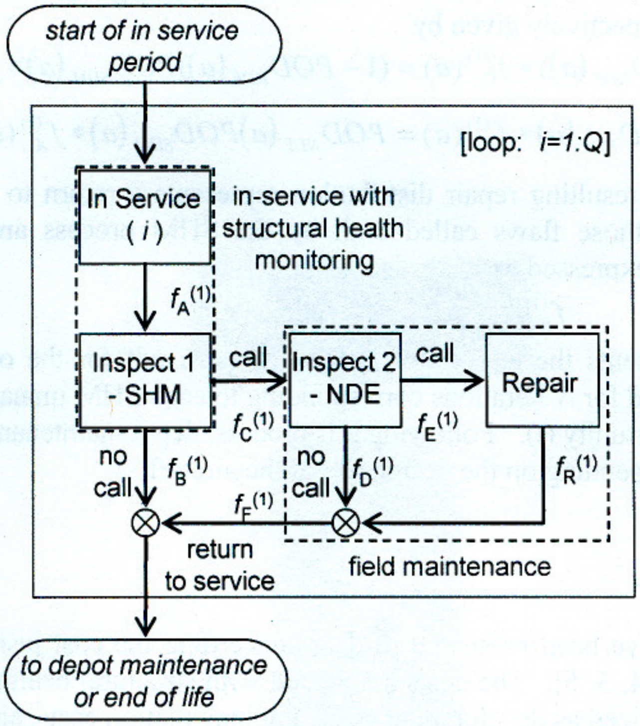

Figure 2. Flow diagram representing model of in-service period with SHM and optional in-field maintenance.

In this formulation, $F_p^{(1)}$ and $f_p^{(1)}$ are defined as the cumulative density function (cdf) and probability density function (pdf) respectively, representing the flaw size distribution for feature type 1 (given by the superscript) at stage p (given by the subscript) in the inspect-repair sub-process. The subscripts A, B, and C are associated with flaw size distributions for the start of the SHM process, the portion associated with no call made (flaws not found), and the portion associated with a call made (flaws detected). $P_{SHM}^{(1)}$ is defined as the percentage of the pdf called (flaws detected) by the SHM process, and is given by

$$P_{SHM}^{(1)} = \int_0^\infty POD_{SHM}(a) f_A^{(1)}(a) da, \quad (2)$$

where a is associated with flaw size and $POD_{SHM}(a)$ is the probability of detection function for the SHM process. The corresponding 'no call' and 'called' distributions resulting from SHM are respectively given by

$$f_B^{(1)}(a) = (1 - POD_{SHM}(a)) * f_A^{(1)}(a), \quad (3)$$

$$f_C^{(1)}(a) = POD_{SHM}(a) * f_A^{(1)}(a). \quad (4)$$

A secondary inspection given in block 'Inspect 2 - NDE' can also be evaluated in a similar fashion, where $P_{NDE}^{(1)}$ is defined as the percentage of the pdf called (flaws detected) by the NDE procedure, and is given by

$$P_{NDE}^{(1)} = \int_0^\infty POD_{NDE}(a) f_C^{(1)}(a) da = \int_0^\infty POD_{NDE}(a) POD_{SHM}(a) * f_A^{(1)}(a) da. \quad (5)$$

The corresponding 'no call' and 'called' distributions resulting from the secondary NDE procedure are respectively given by

$$f_D^{(1)}(a) = (1 - POD_{NDE}(a)) * f_C^{(1)}(a) = (1 - POD_{NDE}(a))POD_{SHM}(a) * f_A^{(1)}(a)\,, \quad (6)$$

$$f_E^{(1)}(a) = POD_{NDE}(a) * f_C^{(1)}(a) = POD_{NDE}(a)POD_{SHM}(a) * f_A^{(1)}(a)\,. \quad (7)$$

For this example, the resulting repair distribution represents a return to the original state of the part for those flaws called both by the SHM process and the NDE technique, and can be expressed as

$$f_R^{(1)}(a) = P_{NDE}{}^{(1)} \cdot f_{R\_EIFS}^{(1)}(a)\,, \quad (8)$$

where $f_{R\_EIFS}(a)$ represents the equivalent initial flaw size pdf for the original part. This process is repeated for N iterations corresponding to each SHM manager decision and maintenance opportunity (i). Following this process, depot maintenance or end of life may be reached depending on the design life of the aircraft.

SHM COST MODEL

Limited studies have been presented to date concerning the cost justification for SHM applications [3, 4, 5, 6]. The costs associated with structural health monitoring systems can be categorized as development costs, implementation costs, and in-service costs. Development costs include any initial research and system development work for a particular application. Implementation costs are associated with the fixed initial cost for purchasing and installing the on-board SHM system and for performing validation studies to satisfy reliability and certification requirements. Both development and implementation costs are expected to be much higher for SHM system with respect to those of NDE techniques, given the increasingly difficult system requirements concerning inspection and reliability. Lastly, in-service costs can include the additional cost of fuel due to added SHM system weight, data interpretation labor costs, SHM maintenance costs, and the cost of secondary inspection and unnecessary repair due to false calls or unnecessary calls when flaws are very small. While in-service costs of SHM systems are expected to be low in relation to those of NDE procedures, design-time consideration must be given to the possibility for such costs to be significant in order to minimize their impact on total life cycle cost.

CASE STUDIES FOR DEMONSTRATION

Two case studies are presented to demonstrate the capability of the software platform and to gain a better understanding of the dynamics of the SHM system model. The models for flaw growth and repair represent typical life prediction and maintenance conditions for multi-layer aircraft structures which are subject to fatigue cracking around fastener holes. The first study explores the effect of varying the frequency of SHM calls for a fixed total service life. Figure 3 shows the simulated results for probability of failure (POF) and cumulative maintenance cost as a function of time and number of SHM cycles. A higher frequency of SHM calls will result in

higher life-cycle cost, for two reasons. First, the total cost associated with labor hours for data interpretation increases with the frequency of SHM calls. The second source for higher costs occurs over the later part of the in-service period, where non-critical flaws are called by the SHM system. Ideally, minimizing the frequency of calls while maintaining an acceptable probability of failure is a fundamental design principle for minimizing life-cycle costs. Alternatively, higher frequencies of SHM calls can significantly improve reliability. This strategy is particularly valuable when the SHM system is designed to only detect very large flaws, the crack growth model is nonlinear, or uncertainty is present in the crack growth model parameters.

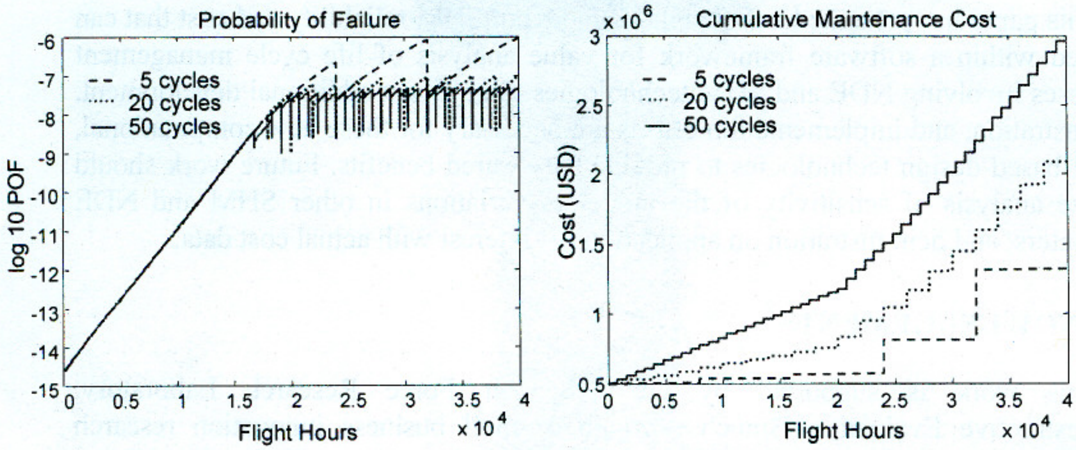

Figure 3. Probability of failure and cumulative maintenance costs time histories for three cases

A second case study explores degradation in SHM system performance over time. The total service life was divided into ten service periods separated by nine maintenance events consisting of SHM data processing and subsequent field inspection and repair. A variable probability of detection was assigned to the SHM system as follows: maintenance events 1 – 5 were assigned the SHM POD labeled t_0 in Figure 4(a), t_1 was assigned to the SHM system at maintenance event 6, t_2 to maintenance event 7, and t_3 to maintenance events 8 and 9. Figure 4(b) compares the

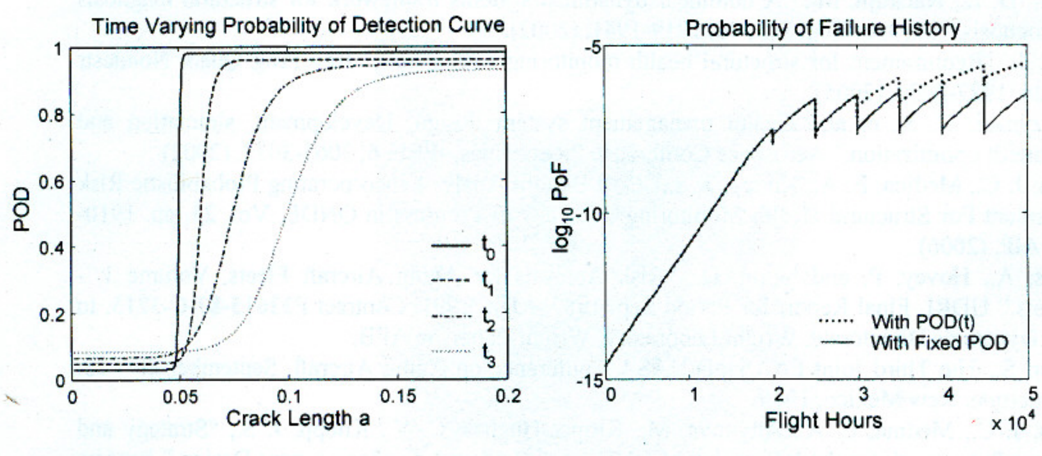

Figure 4. Effects of SHM system deterioration: (a) time varying POD, (b) resulting POF

probability of failure history for the time varying SHM POD case just described to that of a case where the POD of the SHM system is fixed to that labeled t_0 in Figure 4(a). Figure 4(b) shows that the variable POD case results in an undesirable increase in probability of failure. Not shown here is the fact that the total cost for the variable POD case is lower than that of the fixed POD case, because finding and repairing fewer flaws results in lower costs at the expense of a higher risk of failure.

CONCLUSIONS

This paper has presented a probabilistic model of SHM reliability and cost that can be used within a software framework for value analysis of life cycle management processes involving NDE and SHM technologies. Significant additional development, demonstration, and implementation efforts are necessary for these new computational, model-based design technologies to provide the desired benefits. Future work should involve analysis of sensitivity of the model to variations in other SHM and NDE parameters, and demonstration on applications of interest with actual cost data.

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